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Boston Harbor Dredged Material Capping Simulation

by Landris T. Lee, Jr.

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) documents geotechnical research performed by the U.S. Army Engineer Research and Development Center (ERDC) specifically for the Boston Harbor Navigation Improvement Project. Laboratory modeling of the subaqueous sand capping process was conducted to allow a comparison to field performance of sand capping dredged material in a confined aquatic disposal cell.

BACKGROUND: The practice of covering subaqueous contaminated disposed dredged material with a clean isolating material has been conducted since the 1970s, and is a cost-effective alternative to other disposal options (Palermo et al. 1998). Capping has been especially suitable for isolating disposed contaminated dredged material in confined aquatic cells such as pre-existing subaqueous pits where the dredged material is laterally confined. An isolating cap typically composed of clean sand is superimposed on the top of the previously placed dredged material in such a fashion as to encapsulate the exposed surface of the dredged material (Figure 1). Special consideration must be taken to prevent geotechnical instability induced by the addition of an overlying sand cap that often has a greater density than the underlying dredged material. A goal of successful cap design is to preserve geotechnical stability during and after cap placement. To design a cap that achieves this goal, information about the underlying dredged material's strength behavior is needed.

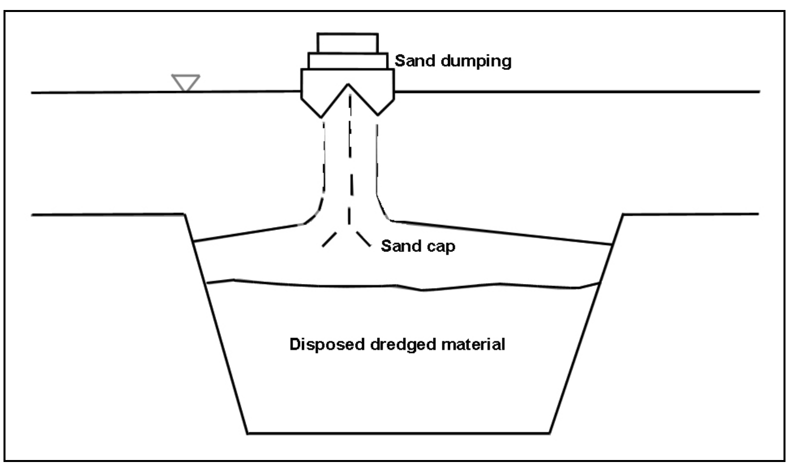

Figure 1. Encapsulating contaminated dredged material placed in a confined cell

Geotechnical Aspects of Dredged Material Sediment Caps: Typical dredged material sediments consist of fine-grained soils having high water contents and low shear strengths. Since optimal geotechnical stability is achieved using soils with low-water contents and high shear strengths, the challenges are greater for designing, constructing, and monitoring

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Boston Harbor Dredged Material Capping Simulation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers (USACE),Coastal and Hydraulics Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

subaqueous dredged material capping projects. Geotechnical properties must be well defined and become especially critical if the capping process is expedited (Clausner et al. 1998).

Very few geotechnical evaluations have been conducted for dredged material capping projects, and generally, the cap design is empirically based on field experience (Rollings 2000). During the Boston Harbor project, advances in evaluating the geotechnical preperformance of dredged material sediment caps were made utilizing laboratory analytical and physical modeling techniques to simulate the capping process and predict the minimum strengths needed prior to capping.

Boston Harbor Project: The Boston Harbor Navigation Improvement Project included maintenance dredging of the main ship channel and tributaries conducted through the spring of 2000. Contaminated dredged material was placed in several subaqueous confined aquatic disposal cells located in the channel which were capped with clean sand. Dredged material sediment samples were collected at various intervals during the disposal and capping operations, and the samples were analyzed for geotechnical parameters (SAIC 2000; Myre, Walter, and Rollings 2000). In addition, some of the geotechnical construction and monitoring techniques during disposal and capping operations were evaluated (Fredette et al. 2000).

Geotechnical analysis of some capped cells indicated that the dredged material placed in those cells most likely had insufficient upper surface bearing capacity to adequately sustain the induced sand cap weight. One cell in particular (cell M2), which performed adequately, was chosen for a more detailed performance analysis prior to, during, and after the cap was placed (Myre, Walter, and Rollings 2000). Cell M2 observations showed that extending the dredged material sediment consolidation period prior to capping allowed the sediment shear strength to increase sufficiently to adequately resist the superimposed cap weight. Changes in sediment characteristics and material properties most critical to predicting cap performance were observed during field sampling efforts. As an example, changes in sediment consistency were monitored by dropping grab sample contents onto a flat surface and observing the spreading diameter and changing sample height. The cell M2 dredged material sediment was undergoing in situ self-weight consolidation while achieving higher shear strengths and lower water contents during the 5-month period prior to sand capping. Just prior to sand capping, sediment samples were taken, and it was determined that the upper 3-ft (1 m) layer of precapped sediment had achieved a shear strength of about 20 lbf/ft^2 (1 kPa), with water content (weight of water per weight of solid) averaging 100 percent in the upper 20 in. (50 cm). The cell M2 was then capped with a 3-ft (1-m) layer of fine sand, and postcap samples indicated that the underlying dredged material sediment adequately resisted the overlying sand cap weight.

CONFINED AQUATIC DISPOSAL CELL CAP LABORATORY SIMULATIONS:

Simulations were performed using analytical modeling with geotechnical software, physical modeling with a centrifuge, and laboratory testing to obtain material properties. The goals of the simulations were to apply modeling techniques to obtain geotechnical performance parameters and characteristics enabling better understanding of the sediment capping process; enable better predictions of required minimum geotechnical parameters necessary for capping; and expand upon a potential field monitoring method to enable faster characterization of sediment properties.

Sediment Material Characteristics Testing: A surrogate dredged material having similar geotechnical properties was chosen to represent the actual contaminated sediment material. Homogeneous soil types of lean clay (CL), fat clay (CH), white kaolinite clay (CL), and silt (MH) were mixed with varying amounts of water to achieve a water content ranging from 31 percent to 102 percent. Each soil's remolded undrained shear strength was taken at the corresponding water content using the laboratory miniature vane shear device (ASTM 2000). The kaolinite soil was chosen as the surrogate dredged material for physical modeling in the centrifuge based on the laboratory test results most closely resembling those from the cell M2 sediment.

An expanded method for obtaining in situ sampled sediment properties consisted of modifying the flat board method used at Boston Harbor's cell M2. A device similar in function to the concrete slump test method (ASTM 1999) was utilized for the dual purpose of correlating undrained shear strength to water content as well as providing a method to monitor those properties for the physical model. The remolded soil was placed in the slump cylinder, filled to the top, and leveled. The cylinder was then slowly lifted in an upward motion similar to the concrete slump test method, and the height difference (slump) was measured after the soil flowed out and reached its equilibrium height (Figure 2). The dredged material slump cylinder may be utilized as an indication of soil slurry consistency, which is related to the soil water content and shear strength. Figure 3 illustrates the relationships between soil consistency (slump), water content, and undrained shear strength for the kaolinite soil.

Figure 2. Slump test of kaolinite soil with approximate shear strength of 25 lbf/ft^2 (1.2 kPa)

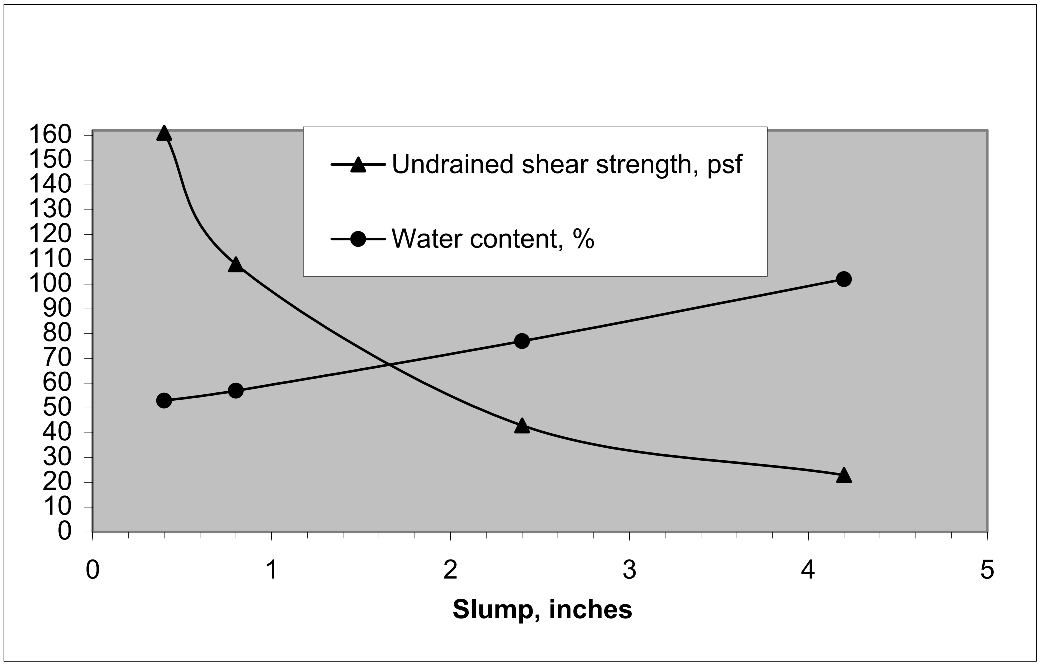

Figure 3. Kaolinite soil slump, water content, and shear strength relationships. Ordinate units are pounds force per square foot (lbf/ft^2) or water content percentage (%). (To convert pounds force per square foot to kilopascals, multiply by 0.04788026)

Analytical Modeling of the Confined Aquatic Disposal Cell: A two-dimensional finite element program developed at ERDC, STUBBS, was available to model the geotechnical parameters assigned to simulate dredged material sediment underlying sand cap layers. The software simulated the complete cap placement process by sequentially placing layered elements until the final confined aquatic disposal cell geometry mesh was created (Figure 4). The dredged material was modeled as a homogeneous frictionless material with a cohesion parameter equal to the undrained shear strength. This representation was based on the assumption that in the initial nonconsolidated state, the material would be similar to the as-disposed uniform state. The physical modeling with the centrifuge served to confirm this conservative assumption. The stresses and displacements were computed for the partially filled cell after each layer was placed. The geotechnical stability of the capped cell was characterized by the extent of plastic yielding within the dredged material. Initial upper strength boundary conditions were assigned, and a series of computations were performed. As the shear strength of the dredged material was reduced toward a lower bound, the yielding deformation pattern grew into a state of failure. As the lower bound strength was approached, the model became unstable, and eventually the stress computations did not converge.

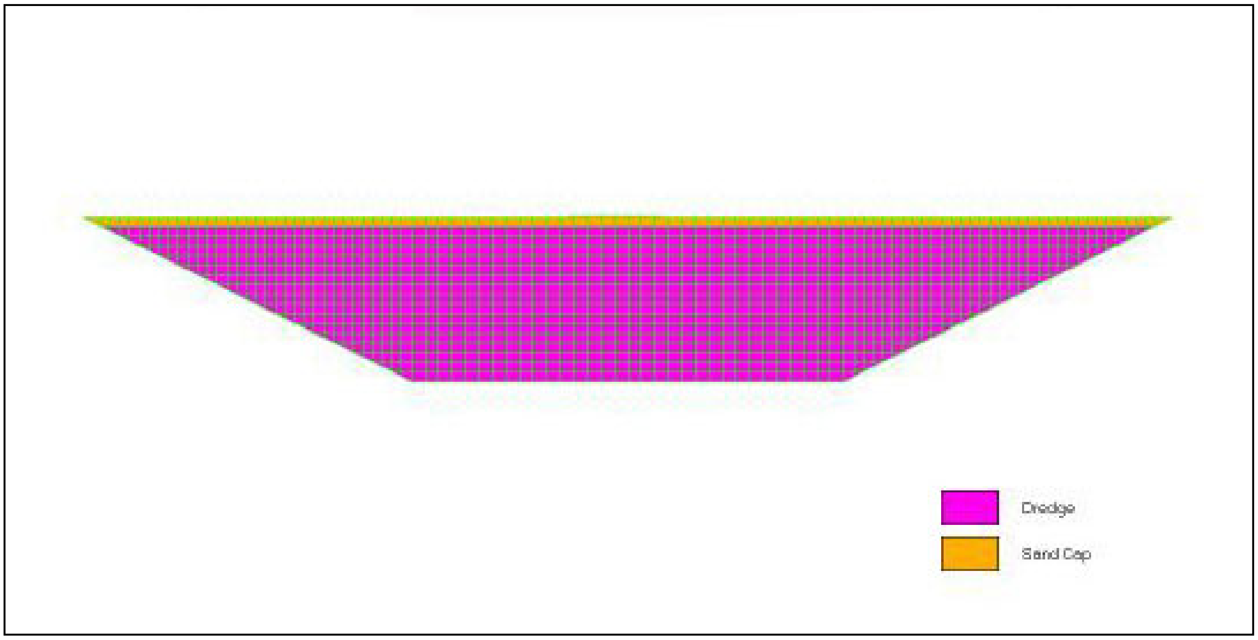

Figure 4. STUBBS finite element mesh (purple indicates the dredged material sediment, and orange indicates the overlying sand cap)

The surface geometry of the overlying sand layer was modeled after in situ depth soundings at cell M2, which indicated that the surface slope of the sand typically varied by a few percent. The mesh elements in the sand layer were thickened to create a small 100-ft (33-m) wide mound on the sand surface. The mound reached a maximum height of 0.5 ft (0.15 m) above nominal elevation of the sand surface to create a 1 percent slope (Figure 5).

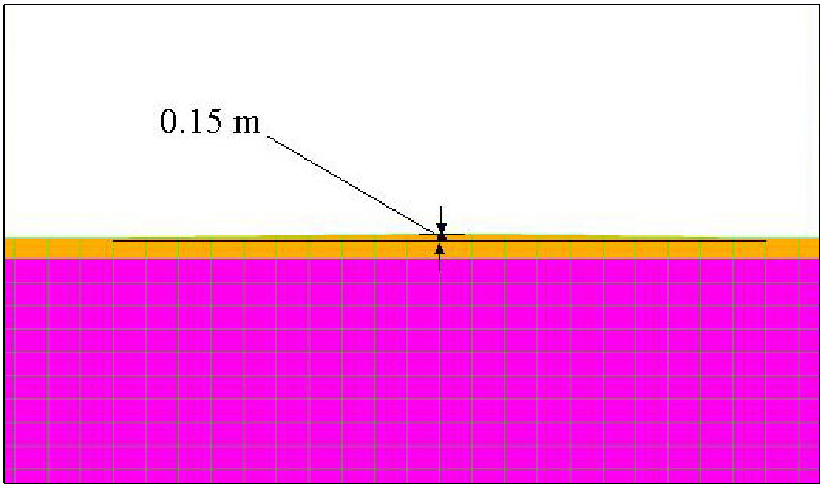

Figure 5. STUBBS finite element mesh showing the maximum height variation of the overlying sand cap

Significant yielding under this slight mound was observed when the assumed strength of the clay sediment was decreased to 17 lbf/ft^2 (0.8 kPa) (Figure 6).

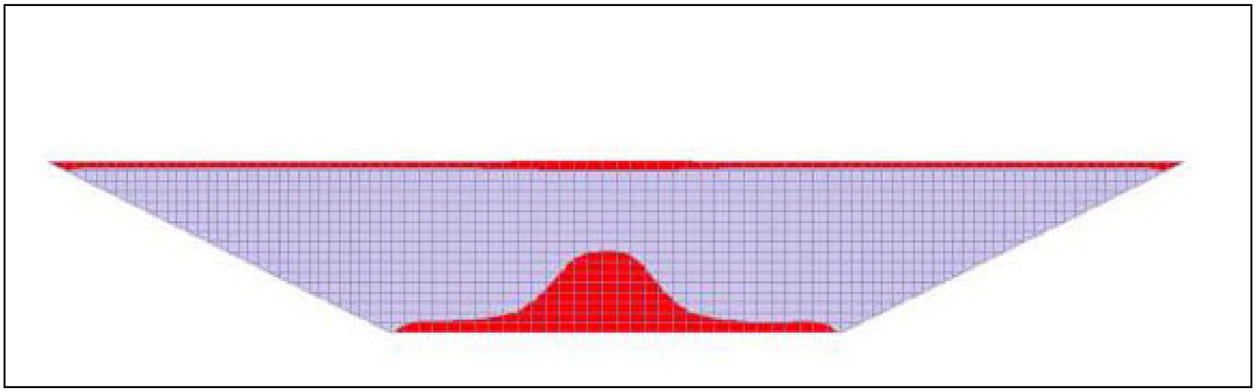

Figure 6. STUBBS finite element mesh indicating onset of failure for undrained shear strength at 17 lbf/ft^2 (0.8 kPa). Red zone indicates dredged material stress failure development

At 5 lbf/ft^2 (0.2 kPa) the modeled deformation yielding indicated an essentially complete failure mechanism, although an equilibrium solution was maintained (Figure 7).

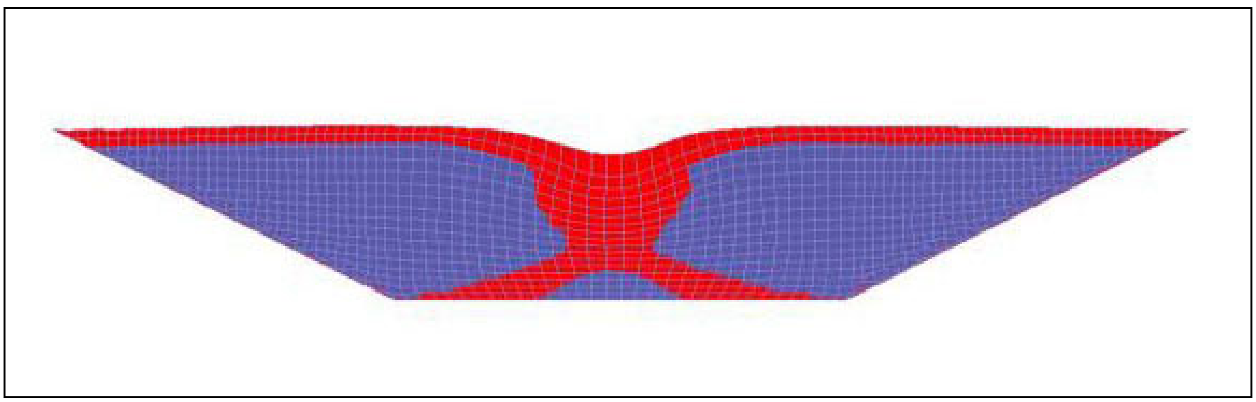

Figure 7. STUBBS finite element mesh indicating deformation failure for undrained shear strength at 5 lbf/ft^2 (0.2 kPa). Red zone indicates dredged material stress failure

At 2.5 lbf/ft^2 (0.1 kPa) convergence in the solution could not be obtained. The deformation pattern in all modeled cases indicated that the principal plane of shear developed along the base of the confined aquatic disposal cell rather than within the fill material, suggesting that the size and shape of the cell bottom controlled the critical shear surface. From these modeling results it appeared that an undrained shear strength of about 20 lbf/ft^2 (1 kPa) was a reasonable criteria for dredged material strength prior to capping provided the cap thickness can be maintained to the tolerance of the cell M2.

Physical Modeling of the Confined Aquatic Disposal Cell Capping Process: The numerical modeling results provided insight into the lower range of required undrained shear strength in the dredged material and the results appeared to be consistent with cell M2 field performance. However, the numerical model was based on numerous assumptions, and did not account for possible pore pressure effects related to pore water upwelling as the consolidation process took place. The present scope of numerical modeling did not address such transient effects, although STUBBS has the capability to deal with such effects including coupled flow

and deformation (consolidation). In addition, field sampling efforts did not include pore-pressure observations or measurements. To observe cell cap performance due to these effects, and to help validate the analytical modeling effort, it was necessary to perform physical modeling.

Physical modeling on the geotechnical centrifuge provided a link between the numerical computations and field observations. The centrifuge intensifies the gravity-induced body forces to allow dimensionally correct scale models that more accurately reflect the physical processes. Physical modeling was accomplished using the U.S. Army Centrifuge Facility at ERDC (Figure 8).

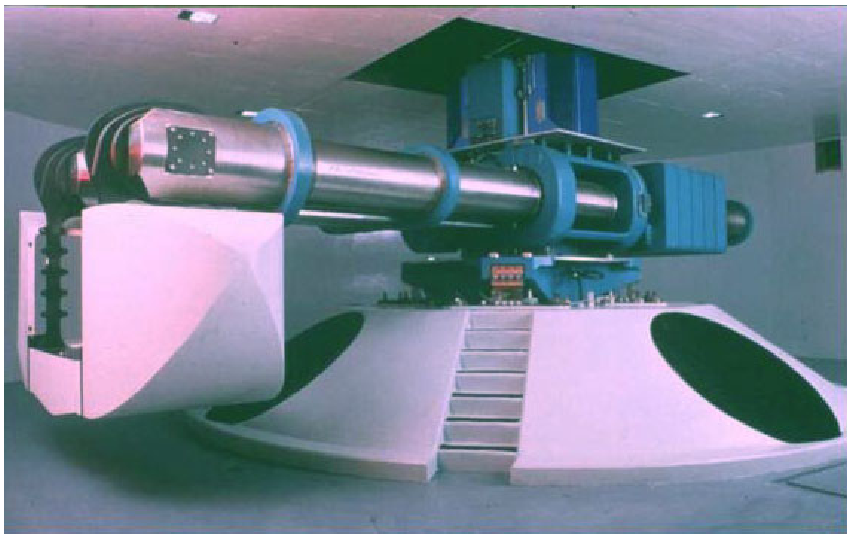

Figure 8. U.S. Army Centrifuge Research Facility at ERDC

A rectangular box was constructed to contain the surrogate contaminated dredged material and sand cap (Figure 9). The clay-water mixture representing the dredged material fill was placed at a water content which allowed an undrained shear strength of between 20 to 30 lbf/ft^2 (1 to 1.4 kPa), based on previous laboratory testing results. At this lower strength range, based on the analytical modeling results, the sand cap would be assumed to be minimally stable. To simulate the physical layout of cell M2, the model was built to scale proportions for which a unit model length equaled 10 length units in the full-scale prototype cell M2. During centrifuge flight, a specially designed sand dispenser was operated in a fashion imitating the two-dimensional dump scow placement process for the prototype cell M2 sand cap.

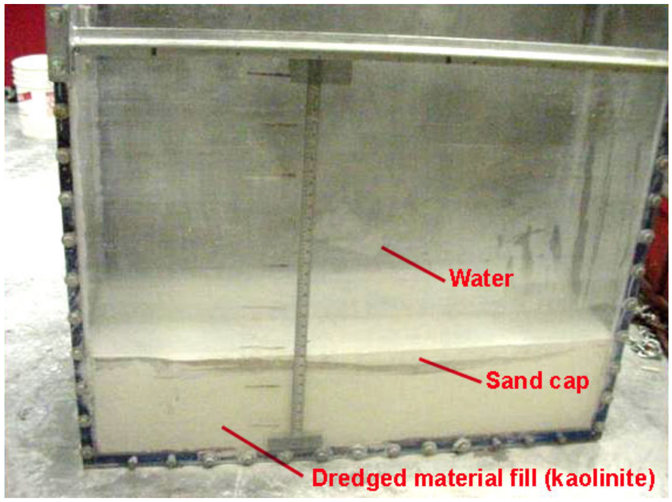

Figure 9. Physical test model flown on the centrifuge

After flight, the soil model was analyzed and the layer geometry was noted (Figure 10). As expected, the sand cap remained stable although significant settlement was observed in the sand surface. This settlement likely occurred due to the time-dependent consolidation process in the kaolinite clay. No significant disturbance in the sand cap was noted due to pore fluid moving upward from the consolidating clay.

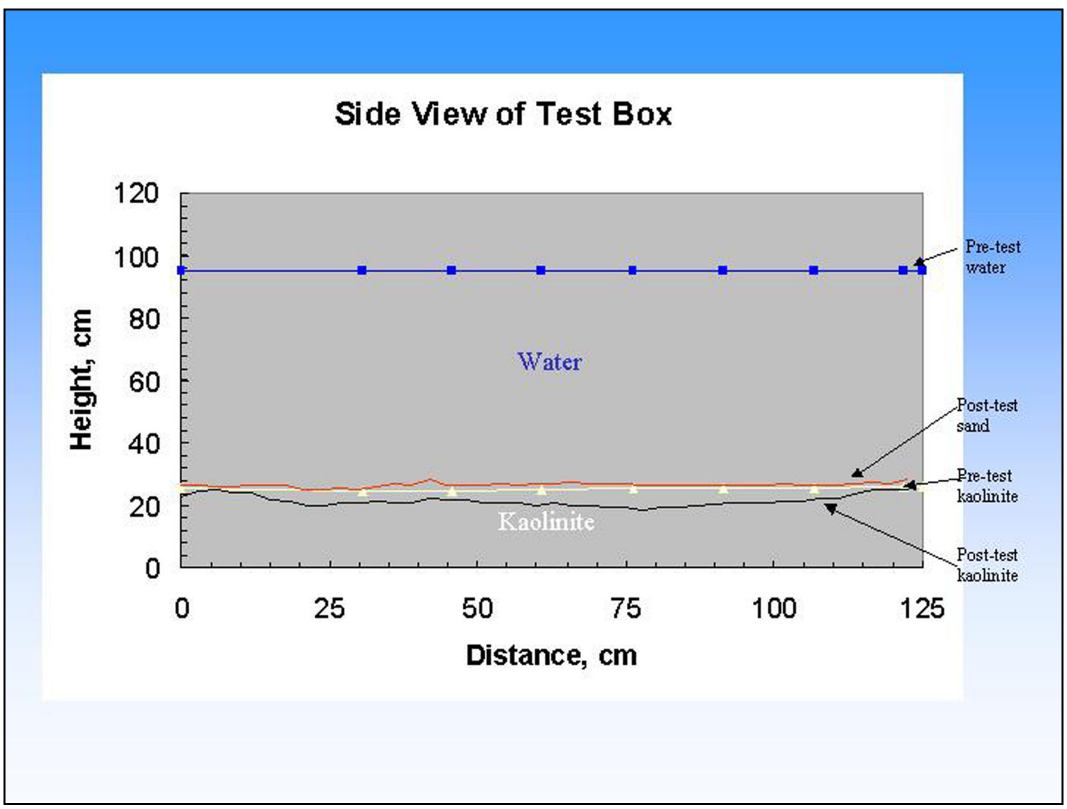

Figure 10. Pre- and post-test sand cap locations in the test model

Summary: The analytical and physical model simulations indicated the sand cap was stable when placed on top of clay material having undrained shear strengths greater than 17 lbf/ft^2 (0.8 kPa) and water contents below 100 percent. Actual cap performance in Boston Harbor's cell M2 appeared to substantiate the model results. The laboratory testing of the clay material indicated that measuring the soil's consistency (slump) correlated to its physical properties such as water content and shear strength may be a promising method adaptable to field monitoring usage.

ADDITIONAL INFORMATION: Questions about this CHETN can be addressed to Mr. Landris T. Lee (601-634-2661, Fax 601-634-3453, Landris.T.Lee@erdc.usace.army.mil); Dr. John F. Peters (601-634-2590, Fax 601-634-3453, John.F.Peters@erdc.usace.army.mil). This work was conducted as part of the Monitoring Completed Navigation Projects Program (Boston Harbor Confined Aquatic Disposal Cell Work Unit). This Technical Note should be referenced as follows:

Lee, L. T., Jr. (2001). "Boston Harbor dredged material capping simulation," Coastal and Hydraulics Engineering Technical Note CHETN VI-36, U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://chl.erdc.usace.army.mil

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